Policy Considerations for Adapting Power Systems to Climate Change

Risks of maladaptation, efforts to integrate local knowledge, and considerations for other policy priorities will help ensure a more robust adaptation process for power systems. Existing modeling tools can be used to provide an assessment of adaptation measures that moves toward incorporating these insights, although future work is still necessary to incorporate factors like cost and risks for imposition of path-dependency.

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I. Introduction

A growing number of authoritative sources have highlighted the importance of considering climate change risks to energy systems. Multiple academic, government, and industry researchers have conducted studies identifying in particular the risks to electric power systems that come from extreme temperatures, sudden and severe weather, and changes in precipitation. Each of these phenomena jeopardize the ability of power systems to balance demand and supply in multiple ways – from creating uncertainty around what levels of system capacity should be built to obstructing the delivery of coal fuels by river barge (Rothstein and Parey, 2011; Dell et al., 2014; Scott and Huang, 2007; Bull et al., 2007; Zamuda et al., 2013; DNV-GL, 2014). Necessarily, these risks imply a need for risk

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mitigation – that is, for adapting power systems to climate change.

Though interest in climate change adaptation of power systems is growing, much of the deliberation over how to adapt power systems has focused upon large-scale investments in relatively fixed capital. Moreover, there does not seem to be much borrowing from adaptation experiences within other sectors and other parts of the world that have been dealing with climate change risks for years, such as water management. The utility responses to Superstorm Sandy provide a good example of this status quo. In the wake of the storm, many of the responses proposed by utilities revolved around so-called ‘‘grid hardening’’ plans; these plans involved relocation, reinforcement, and embellishment of existing infrastructure, at steep costs to the utility and ultimately the ratepayers. While such measures certainly have their merits and in some cases addressed long-standing climate vulnerabilities within the existing power system infrastructure, the plans seemed to give little credit or attention to alternative measures that had played major roles in resilience to the storm such as combined-heat-and-power units (Lacey, 2014). Similar thinking has been applied in the case of other energy networks, particularly natural gas, in which the recommended resilience strategy has been to vertically integrate and increase the density of natural gas pipeline networks (Evans and Farina, 2013).

This article attempts to broaden the discourse around climate adaptation options for the U.S. power sector by presenting insights on climate change adaptation from other sectors and other parts of the world, and by demonstrating via a preliminary analysis ways in which those insights might be integrated into assessments of adaptation measures. This article provides a literature review that derives key points of guidance for climate adaptation generally, and uses a computable general equilibrium tool to illustrate how those insights might be used. Suggestions are made at the end of the article for further research into using these insights in decisions on how to adapt power systems to climate change.

The discourse around climate adaptation options for the U.S. power sector can be broadened by presenting insights on climate change adaptation from other sectors and other parts of the world.

II. Lessons from Climate Adaptation Literature

Despite there being a great deal of promise in the suggestions dominating the industry discourse on adapting power systems to climate change, research in other areas of climate change adaptation reveals key insights that do not yet appear to have found a strong voice. The focus upon major infrastructure investments held by industry practitioners in the adaptation space obscures a myriad of alternatives that have found use in other domains of climate adaptation. Distributed resources, for example, are considered to be a ‘‘relatively small’’ component of the power sectors’ adaptation approach by some utility executives (Lacey, 2014). By contrast, distributed water resources have found to be critical in adaptation to drought conditions in some parts of the world (Laves et al., 2014). In this section, we explore some of these insights and conclude with key takeaways for those researching climate adaptation policies and practices for the power sector.

A. Considering potentials for maladaptation

While certain measures may appear to provide a way to adapt to climate change, these measures can sometimes exacerbate vulnerabilities and risks from climate change in unforeseen ways. This unintended exacerbation is referred to as ‘‘maladaptation.’’ Maladaptation can occur in a wide variety of ways; Barnett and O’Neill (2010) provide a useful typology of

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maladaptive practices from multiple sectors adapting to climate change, a typology that comprises five main categories of maladaptation: (1) incurring high social costs relative to alternatives, (2) imposing path-dependency on resource systems, (3) reducing incentives for further adaptation efforts by private actors, (4) placing undue burdens on already-vulnerable populations, and (5) increasing greenhouse gas emissions, the last of which is maladaptive because it begets the need for further adaptation.

Each of these maladaptation risks bears consideration in the electric power sector. The incurrence of high social costs is demonstrated in the strain of water resources by new power plants built to meet rising climate-driven loads (Rogers, 2013; Union of Concerned Scientists, 2011). Major financial investments involved with enhancing networks, such as PSE&G's $1.2 billion ''Energy Strong'' grid-hardening plan (originally proposed to be $3.9 billion) (Lacey, 2014), can strain fiscal resources that could be used toward other adaptive measures in the future (Vine, 2012). An approach that concentrates large investments into single adaptation measures also creates high risks for stranded costs if the adaptive measures turn out not to be needed, such as the case of stranded power plant fixed costs that occur when customers adopt energy efficiency and distributed generation (National Action Plan for Energy Efficiency, 2007). Increasing the availability of supplies via infrastructure networks, through favorable policies such as rate-of-return regulation and master limited partnerships, discourages individual efforts at adaptation. While such policies can enable greater access to power systems and other climate-vulnerable resources like coastal property, subsidies for infrastructure can discourage individuals from finding efficient and less climate-vulnerable ways of satisfying their demands (Filatova, 2014; US Congressional Budget Office, 2012). Moreover, policies around power infrastructure development typically involve spreading the costs over captive ratepayers. Such infrastructure projects are typically more beneficial for some ratepayers than others; the least wealthy ratepayers, who are typically more vulnerable to climate change, are impacted disproportionately by rate increases to cover the cost of infrastructure. Finally, expansion of power and other fossil-based energy system infrastructures can lead to increases in greenhouse gas emissions and beget the need for further adaptation that could otherwise be avoided – in tandem with the other maladaptation risks above.

> *Literature in climate adaptation emphasizes the local scale, both in problem definition and in proposing solutions.*

B. Using local knowledge to solve local problems

Literature in climate adaptation emphasizes the local scale, both in problem definition and in proposing solutions. First, the literature emphasizes the locality-specific nature of climate change problems. Even within regions, such as the Murray-Darling river basin in Australia, climate change has caused a re-distribution of natural resources such that some localities become water-richer while other localities become water-poorer (Saintilan et al., 2013). Thus, broad-scale policies that promote specific adaptive measures across heterogeneous localities are likely to be ineffective at promoting the context-specific adaptations necessary (Filatova, 2014; Smith, 2010). Moreover, policies made centrally can have unintended consequences of constraining adaptation locally; resource protection policies (Saintilan et al., 2013; Ledoux et al., 2000), planning restrictions (Naess et al., 2005), and even regulations on budgetary cycles (Lorenzoni et al., 2000) can create barriers to the responsiveness of local regions to local climate problems. Barriers to climate change adaptation in a given locality can often be driven by factors other than the local climate, however. The contentiousness of local politics in coastal management, for example, has been found to inhibit implementation of adaptive measures (Filatova, 2014).

Given the locality-specific nature of adaptation issues, much of the adaptation literature explores the use of locality-specific knowledge toward climate change adaptation. Among rural pastoralists, for example, knowledge of the local environment has been found to yield effective ways of adapting to climate change (Fu et al., 2012). Policies involving market-based instruments have been found to be effective at capitalizing upon local knowledge and accounting for heterogeneity both in local problems and local preferences (Filatova, 2014; Saintilan et al., 2013). However, centrally made requirements for resource management practices have been found to spur innovation and increase local knowledge, for example by inducing innovation through requirements for storing resources (Fu et al., 2012). More generally, centrally made policies can add value to local adaptation by clarifying priorities and providing resources that are beyond the scale owned by the adapting locality itself (Urwin and Jordan, 2008; Glaas and Juhola, 2013).

Many sources agree that adaptation policies should be designed around knowledge – learning from every implementation experience and allowing for adjustments to reflect new knowledge, regardless of whatever particular concrete adaptation measures are pursued. Dupuis and Biesbroek (2013, p. 1483) calls this the creation of an ''enabling institutional environment,'' one in which knowledge is constantly developed and shared and policies and behaviors are constantly being updated to reflect this knowledge. The South East Queensland government's responsiveness to follow-up estimates of the excessive costs and conservation-underperformance of its rainwater storage tank rebate policy, which resulted in the repeal of that policy (Laves et al., 2014), serves as an example of an enabling environment. Similar terms used to describe enabling environments are ''adaptive capacity'' (Vine, 2012; Moser and Luers, 2008; Wilbanks, 2005), and ''policy capacity'' (Craft et al., 2013; Williams and McNutt, 2013). Since few adaptations can yet be evaluated ex-post, much of the literature focuses upon policy options for creating enabling environments and adaptive capacity.

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C. Placing adaptation within other private and policy-related goals

Even when climate adaptation is recognized as a priority, it competes with other priorities held by both private actors and policymakers. While this situation typically results in conflict between policy goals (The Economist, 2010), adaptation has often arisen out of synergies with other public and private goals. In a comprehensive review of adaptation activities in the United Kingdom, Tompkins et al. (2010) finds that much climate adaptation there has been primarily driven by concerns other than climate adaptation, such as cost savings and economic development benefits. These ''co-benefits'' are found to be strong drivers of adaptation in other work, such as analyses of adaptive responses in Australia (Saintilan et al., 2013; Laves et al., 2014; Smith et al., 2011). Even co-benefits of social reinforcement and norm-following are used to drive adaptation (Barnett and O'Neill, 2010). Moreover, this synergy between adaptation and other policy goals is found among

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policymakers; Aggarwal (2013) finds that policymakers in Delhi co-opted the national climate adaptation agenda with policies promoting both adaptation and local economic development. Overall, in analyses of power system adaptation, it should be remembered that each adaptation measure brings with it a unique array of co-benefits and unforeseen costs that have implications for other policy goals. Adaptation measures should be evaluated against all criteria defined by the array of policy goals in order to identify synergies and unforeseen damages.

III. An Example of Integrating Adaptation Perspective into Proposed Policies: Forecasting Scenario Outcomes under Demand Disturbance with GT_NEMS

The next segment of our study responds to some of the key adaptation considerations outlined above by offering an example of a more integrated analysis of adaptation strategies. Given that adaptation should be considered within the context of other policy goals and the potential unforeseen outcomes that may occur as a result of adaptation measures, integrated analyses become of value when deliberating over which adaptation measures to choose. Such analyses bring out obscure interactions between adaptation measures and the environments into which they are introduced. In this way, integrated analyses can highlight both potentially unforeseen impacts of adaptation measures and the implications of adaptation measures for other policy goals.

To perform such an integrated analysis, we use the Georgia Tech National Energy Modeling System (GT_NEMS), a tool suited to illustrate the value of an integrated assessment. GT_NEMS is a computable general equilibrium model that performs forecasts of the United States' energy economy. As such, GT_NEMS is well suited for understanding economic feedback loops that provide pathways for adaptation measures to produce second-order and tertiary effects, as well as the economic and energy resource implications of various adaptation measures.

The following sections describe the structure of NEMS and the construction and bases of the scenarios used to perform integrated adaptation assessments.

A. Methodology

GT_NEMS is a CGE model based on the 2014 distribution of the Energy Information Administration (EIA)'s National Energy Modeling System (NEMS), which generated EIA's 2014 *Annual Energy Outlook* (EIA, 2014a). The Annual Energy Outlook forecasts energy supply and demand for the U.S. through 2040. Other than modifications necessary to operate the NEMS model on networked servers at the Georgia Institute of Technology, GT_NEMS is equivalent to NEMS and produces forecasts that deviate less than 1 percent from the AEO 2014. GT_NEMS is thus documented by way of reference to the documentation for NEMS.[1]

GT_NEMS models electric power systems through a regional planning approach that makes use of one module, the Electricity Market Module (EMM), and four sub-modules (EIA, 2014b). The EMM divides the U.S. into 22 regions based on NERC regional boundaries.[2] The EMM performs separate projections of power demand and the cost-minimizing supply necessary to meet that demand for each region. In computing estimates of cost-minimizing supply choices, the EMM uses survey data from EIA's Form 860, 861, and 923 surveys, as well as NERC projections and

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data from FERC Form 1. These inputs are used to characterize end-use load shapes, costs and performance of capacity types, and other key variables within EMM.

B. Scenario design

Our scenario designs consist of the creation of a "disturbance scenario" which is then layered in with several side-cases from the EIA's AEO2014. Our disturbance scenario is designed to represent an unforeseen change to electric power systems in the U.S. Experts convened for the initial Future of Electric Power in the South workshop expressed that analyses of deviations, shocks, and disturbances to equilibrium conditions were becoming of greater value due to the changing climate and global economic development. While equilibrium forecasts using assumptions that reflect prior experience are valuable, the added uncertainty led these experts to support a modeling approach that examines the "future-proof" qualities of various strategic options. That is, in a world of increasing uncertainty, it can be more valuable to know how bad-off (or well-off) power systems will be when the assumptions that underlie their planning suddenly no longer hold due to an unforeseen disturbance.

Developing forecasts of disturbances is a challenging process, especially when working with equilibrium tools, but the design of GT_NEMS allows modeling of a disturbance in electricity demand. Investments in power plant capacity are affected by the expected power demand and expected fuel prices held by system planners. Since long-term investments face the greatest uncertainty in electric power, GT_NEMS uses a "perfect foresight" approach by default to help facilitate the modeling of investments in power plant capacity. The perfect foresight approach allows GT_NEMS' Electricity Capacity Planning (ECP) sub-module to use the power demand projections made by other modules in GT_NEMS. This essentially allows the ECP to "cheat" and avoid coming up with independent expectations of demand. Since power demand and available capacity interact during any single cycle of the model, the demand projections from the prior cycle are used in the ECP's planning for the current cycle. GT_NEMS then iterates through numerical projections until the ECP's expectations of demand (based upon the prior cycle) converge with the demand projections of the current cycle.

To model a disturbance to GT_NEMS' capacity planning, we manually alter the demand expectations of the ECP module. We first deactivate the perfect foresight in the ECP by switching to "myopic foresight," a mode in which the ECP uses the prior two years' average demand growth rate to predict demand for all following years. We then begin overwriting these expectations starting in the year 2020; rather than allowing the ECP to develop its own projections of demand, we use the demand projections from the EIA's Low Macroeconomic Growth AEO2014 side case ("LowMacro"). The LowMacro rates for post-2020 annual power demand growth are on average 0.5 percent lower than the same rates for the EIA AEO2014 reference case. In this disturbance scenario, therefore, less electricity capacity is built than would be appropriate for the rate of demand growth encountered by utility planners. This scenario would be consistent with unexpected temperature changes driving space cooling, space heating, and water heating demands to levels higher than anticipated by utility planners.

C. Adaptation measure definition

The adaptation measure we examine is a comprehensive improvement to U.S. energy efficiency, represented by the assumptions for EIA's Integrated High Demand Technology side case in the AEO2014. In this case, we use assumptions that reflect a greater push for energy efficiency in all sectors and through multiple means. Building code compliance increases beyond the reference case forecast. Fuel efficiency improvements are made for vehicles used to haul freight, e.g. trains, cargo airplanes, and freight trucks, and fuel economy improvement rates in passenger vehicles are also more optimistic. Building shell efficiencies for residential housing improve by 150 percent of the reference case improvements, meeting Energy Star standards by 2023. Commercial building shell efficiencies improve by 125 percent of the reference case value by the year 2040. Finally, several assumptions are made that accelerate the deployment, lower the costs, and increase the efficiency of equipment for the residential, commercial, and industrial demand sectors (U.S. Energy Information Administration, 2014, Table E1).

There are several reasons why a demand energy efficiency scenario such as that represented by the Integrated High Demand Technology side case would be worth considering as an adaptation measure. Energy efficiency has been shown to be a low-cost resource (Granade et al., 2009; Brown and Wang, 2013; Wang and Brown, 2014), which begets little risk of high social, environmental, or other opportunity costs. Some energy efficiency measures, such as building equipment, have a low aspect of path-dependency – they can be removed or redeployed elsewhere as needed (although other measures, such as buildings compliant with building codes, may be less flexible). Similarly, end-use equipment can be deployed relatively quickly in response to changing climatic conditions – in comparison to, say, construction of new power plants or transmission infrastructure. As Vine (2012, p. 96) notes in conclusion, ''…in general, energy efficiency measures and services can be implemented relatively quickly and inexpensively.'' Subsidies and R&D advancement of end-use equipment efficiencies also integrate local knowledge by allowing consumers to decide whether to adopt these technologies based upon the unique situations each faces (although again, building codes do not allow such flexibility for new construction). Energy efficiency has also been specifically recommended as a strategy against energy price shocks (US Congressional Budget Office, 2012), which would likely come with disturbances to power systems caused by climate change.

We present the results of four cases in order to report the impact of these energy efficiency assumptions upon key outcome variables. To avoid confusion with the actual cases whose results are presented here, we refer to this suite of assumptions in the Integrated High Technology side case involving comprehensively greater efficiency as ''the measure.'' We report results for the ''Reference case,'' which mimics the AEO 2014 reference case; the ''High Technology case,'' which mimics the Integrated High Demand Technology case; the ''Disturbance case,'' which introduces the disturbance assumptions described above to the Reference case assumptions; and the ''Disturbance + High Tech case,'' which introduces the Integrated High Demand Technology side case assumptions to the Disturbance case.

IV. Results of Forecasts

Given the key insights outlined in the adaptation literature review

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above, we choose to focus on a few key metrics in the results of our scenario forecast. Because adaptation is a policy goal nested within a host of other policy goals, we take consideration of outcomes relevant to two other policy goals – public health and economic development. In line with the public health policy goal, we examine the outcomes of our adaptation measure with respect to emissions of sulfur dioxide, nitrogen oxide, and mercury pollutant emissions. In line with the economic development goal, we examine outcomes of macroeconomic GDP and values-of-shipment for energy-intensive industries and non-energy-intensive industries. Moreover, since increasing CO_2 emissions is a serious potential maladaptation of adaptation measures targeted toward the energy sector, we examine the CO_2 emissions outcomes by sector and the carbon emissions per capita that result from our adaptation measure. To examine how incentives for autonomous adaptation are affected, we also look at the ways in which energy prices are impacted by our measure. There are several key considerations that we are unable to examine with our methodology, such as the path-dependence of the adaptation measure we examine or the extent to which resources are constrained by this measure and unavailable for future adaptations. Future work in these sorts of approaches, especially future work using NEMS or GT_NEMS to assess adaptations, will incorporate these considerations in numerical detail.

To begin with, Figure 1 shows the public-health-related pollution results for four scenarios – the Reference case, the High Tech case, the Disturbance case, and the Disturbance + High Tech case – in five-year intervals beginning in 2020. Sulfur dioxide emissions decrease drastically in the Disturbance case alone, to below one-third of the reference case values in the later years. In both the Reference case and the Disturbance case, adding the High Technology scenario assumptions does little to shift the sulfur dioxides emissions trajectory, in some cases increasing emissions slightly above reference case values. The same can be said for nitrogen oxide emissions and mercury emissions, although the decline between the Reference case and the Disturbance case is slightly less dramatic. Moreover, nitrogen oxide emissions and mercury emissions in the Disturbance + High Technology case appear to be consistently below the levels seen in the Disturbance case.

Next we examine carbon dioxide emissions in the case of the selected measure in order to assess whether the maladaptation from increasing climate change is likely to occur. Figure 2 displays the trajectories of carbon dioxide emissions for each of the four scenarios. As with emissions of other pollutants, a remarkable decline in carbon dioxide emissions occurs between the Reference case and the

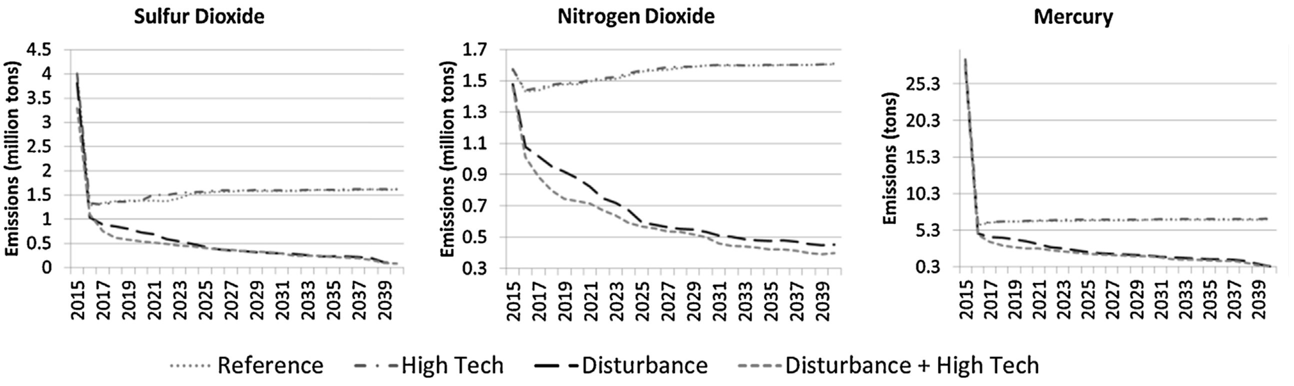

Figure 1: Health-Related Pollutant Emissions for Each Scenario

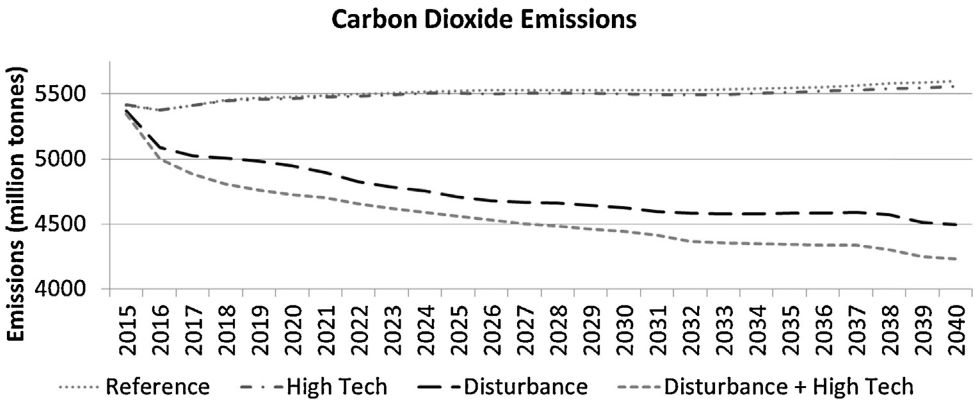

Figure 2: Carbon Dioxide Emissions Trajectories for All Four Scenarios

Disturbance case. Adding the High Technology case assumptions reduces the carbon dioxide emissions further in both the Reference and Disturbance cases, although the difference between the Disturbance case and the Disturbance + High Tech case is greater than the difference between the Reference case and the High Tech case. This suggests additional marginal carbon emissions reductions are gained when the measure is applied in the case of a disturbance.

From examining the demand sector results, however, we see that the impacts of the High Tech assumptions are not spread evenly throughout the sectors. Table 1 shows the carbon emissions outcomes for each of three demand sectors. We see that most of the emissions reduction gains from the High Tech assumptions are concentrated in the Residential Demand sector, in which the differences at each interval between the Disturbance case and the Disturbance + High Technology case are greatest across the three sectors (especially when taken as a percentage). The Industrial Demand sector appears to gain the least in terms of emissions reductions from the application of the measure. The Commercial Demand sector lies between Residential Demand sector and the Industrial Demand sector in terms of its marginal emissions reductions, when comparing between the Disturbance case and the Disturbance + High Technology case.

To establish whether the measure examined here creates disincentives for autonomous adaptation, we look at the overall energy intensity

Table 1: Carbon Dioxide Emissions Outcomes for Three Demand Sectors (in million tonnes)

	Reference Case	High Technology Case	Disturbance Case	Disturbance + High Technology Case
Residential Demand				
2020	1053	1022	879	785
2025	1063	1019	795	718
2030	1072	1029	775	686
2035	1077	1039	752	653
Commercial Demand				
2020	950	949	781	716
2025	985	974	719	675
2030	1011	984	713	650
2035	1039	998	710	631
Industrial Demand				
2020	1688	1709	1520	1479
2025	1752	1787	1496	1491
2030	1762	1802	1485	1479
2035	1751	1793	1467	1442

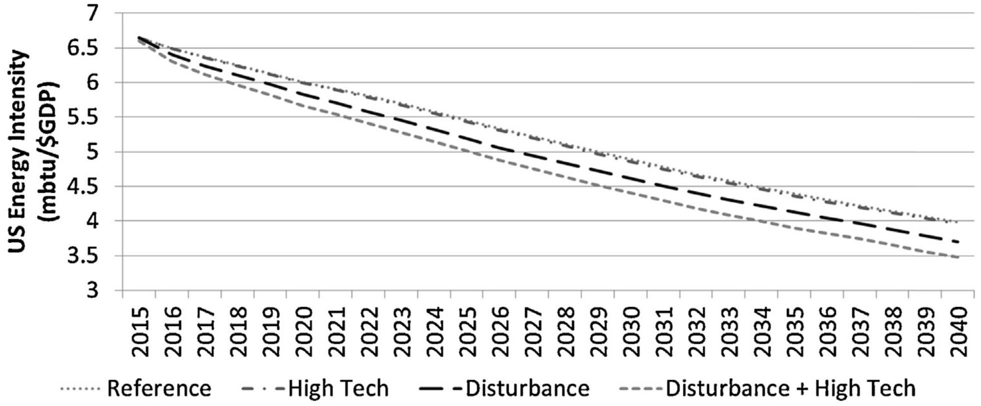

Figure 3: Macroeconomic Energy Intensity Forecasts for the Four Scenarios

outcomes. Since the measure is efficiency-focused, it may create perverse incentives to consume more energy via a rebound effect, which could both increase GHG emissions and discourage conservation behaviors. We examine the overall energy intensity of the economy for signs that the measure applied has actually resulted in either of these effects. Figure 3 displays the energy intensity forecasts of the four scenarios. While there appears to be little difference between the Reference case and the High Technology case, the Disturbance case alone appears to encourage some energy-efficient behavior. Moreover, the Disturbance + High Technology case appears to exhibit a reduction in energy intensity below the level of the Disturbance case. Thus it appears that in the presence of a disturbance, and perhaps only in the presence of a disturbance, our measure is likely to yield macro-efficiency improvements rather than creating perverse incentives or discouraging autonomous adaptation.

Out of consideration for economic development goals, we also examine the real GDP outcomes for the nation and values-of-shipment for energy-intensive industries and non-energy-intensive industries. Table 2 provides the real GDP results of the four scenarios. Real GDP is slightly depressed in the Disturbance case, relative to the reference case. The High Technology Case appears to produce higher GDP than the Reference Case. The Disturbance + High Technology case brings real GDP into closer alignment with the Reference case GDP, however, and is consistently greater than the real GDP under the Disturbance case alone. Thus it seems that the measure has positive economic development benefits in the case of a disturbance.

Taking a closer look into industrial impacts reveals that the measure can actually cause a boost in economic development outcomes for some industries. Table 3 gives the breakout of values-of-shipment by energy-intensive industries and non-energy-intensive industries. While we see the same trend in values-of-shipment being slightly lower in the Disturbance case than in the Reference case, we observe that the Disturbance + High Technology case actually shows values of shipments improving beyond the Reference case for non-energy-intensive industries.

Table 2: Real GDP ($2005 billion) for the US across All Four Scenarios

	Reference Case	High Technology Case	Disturbance Case	Disturbance + High Technology Case
2020	16,753	16,758	16,681	16,662
2025	18,770	18,772	18,676	18,727
2030	21,136	21,143	21,032	21,147
2035	23,747	23,758	23,619	23,733

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Table 3: Values-of-Shipment ($2005 billion) for Industries Classified by Energy Intensity

	Reference Case	High Technology Case	Disturbance Case	Disturbance + High Technology Case
Energy-Intensive Industries				
2020	1,932	1,933	1,897	1,899
2025	2,082	2,082	2,037	2,060
2030	2,171	2,171	2,121	2,152
2035	2,237	2,239	2,188	2,209
Non-Energy-Intensive Industries				
2020	3,804	3,805	3,746	3,744
2025	4,386	4,385	4,319	4,392
2030	4,975	4,975	4,911	5,056
2035	5,542	5,547	5,489	5,652

Energy-intensive industries benefit from the measure, as well, recovering some of the value-of-shipment lost to the disturbance.

Finally, to assess potential for the maladaptation of exacerbating vulnerabilities to climate change, we examine the impact of our measure on electricity prices. Since electricity prices in the United States are often paid by ratepayers with little ability to choose from where they get their electricity, assessing the impacts of our measure upon electricity prices gives some sense of how the measure might impact the most vulnerable. **Table 4** provides forecast values of electricity prices for the Residential Demand sector, the Commercial Demand sector, and the Industrial Demand sector. We see that the Disturbance case exhibits a noticeable divergence of electricity rates from the Reference case for all three sectors. Adding the High Tech assumptions to the Reference case and the Disturbance case produces little difference; in some years the Disturbance + High Technology case electricity price is higher than the Disturbance case electricity price, while in other years the reverse is true. At the very least, it seems that our measure has little risk of making the most vulnerable worse off through a surge in electricity rates, but these outcomes reveal that the measure will not do much to protect vulnerable populations from the effects of the disturbance.

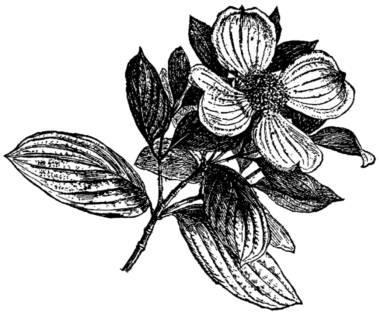
Table 4: Electricity Prices for Each Demand Sector across All Four Scenarios

	Reference Case	High Technology Case	Disturbance Case	Disturbance + High Technology Case
Residential Demand				
2020	0.1236	0.1232	0.1294	0.1315
2025	0.1237	0.1232	0.1343	0.1348
2030	0.1268	0.1264	0.1411	0.1418
2035	0.1295	0.1291	0.1491	0.1481
Commercial Demand				
2020	0.1054	0.1050	0.1115	0.1122
2025	0.1046	0.1042	0.1157	0.1141
2030	0.1073	0.1069	0.1217	0.1216
2035	0.1096	0.1091	0.1296	0.1286
Industrial Demand				
2020	0.0710	0.0708	0.0774	0.0775
2025	0.0722	0.0720	0.0831	0.0802
2030	0.0754	0.0753	0.0906	0.0880
2035	0.0785	0.0784	0.0989	0.0961

A. Interpretation of results and analysis qualifiers

Overall, it seems that our selected measure – an array of energy-efficient technologies promoted via subsidy and advanced by R&D – produces favorable outcomes from many perspectives of adaptation. We see that when these technologies are introduced, several negative impacts of a disturbance to electricity system planning are mitigated. Carbon dioxide emissions are further reduced, real GDP and industry values-of-shipment are improved, and energy intensity declines relative to the case where there is no adaptive measure introduced in the face of the disturbance. Moreover, we see no large increases in electricity prices or emissions of sulfur dioxide, nitrogen oxide, or mercury in the face of our introduced adaptation measure, though the measure also does little to reduce these outcomes.

Several caveats apply to this analysis. Since it represents preliminary work, no assessment of the costs of research and development for achieving more energy-efficient technologies was conducted in this study. It should be noted that the costs of energy-efficiency measures are embedded in the NEMS algorithms. This would be necessary to fill out the picture of how effective the measure could be. Further work on this line of study will include comprehensive-cost-of-development analyses for this and any other measures examined. Furthermore, no assessment of path-dependency imposed by the measure introduced has been done in this study. As mentioned in the literature review, assessing ex ante the potential for path-dependency should be made an important piece of adaptation decision-making. Further work would necessarily include analysis and rigorous arguments for why a given measure may be considered to bear particular risk of imposing path dependency and constraining future adaptation decisions. Without these pieces of information, this article cannot offer final judgment on the value of the adaptation measure studied here. However, the article has demonstrated a means of developing information relevant to key considerations raised by the literature on adaptation in other sectors.



One final caveat, and suggestion for further research, concerns the nature of the study itself. By no means does this study provide comprehensive coverage of all issues related to climate change adaptation in the power system, though the study does demonstrate the potential for existing modeling tools to be useful in that respect. A longer study should involve greater integration of local knowledge in the modeling itself – knowledge of problems, potential solutions, locally held capacities, and local priorities. Because climate adaptation is a location-dependent problem, these factors need to be taken into account. A stakeholder-driven analysis using a tool like GT_NEMS would do more to achieve this key component of adaptation decision-making. In addition, multi-criteria decision-making (MCDM) methods such as the Analytic Hierarchy Process (AHP) and the methods used in De Bruin et al. (2009) might pay a double-dividend. Such methods would both facilitate a decision that incorporates multiple context-specific considerations at once and provide an enabling environment through which stakeholders could learn from one another's knowledge, as is common practice in MCDM processes.

V. Conclusions

The article has raised several key insights from the adaptation literature that should be made part of policy discourses on climate change adaptation measures for the electric power systems. Risks of maladaptation, efforts to integrate local knowledge, and considerations for other policy priorities will help ensure a more robust adaptation process for power systems. In a preliminary effort to show how this might be done, the article has demonstrated that existing modeling tools can be used to provide an assessment of adaptation measures that moves

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toward incorporating these insights. Future work is still necessary to embellish analyses such as the one performed in this article with, for example, full considerations of measure research and development costs and risks for imposition of path-dependency. Additional work should consider how adaptation research processes using tools like NEMS and GT_NEMS could be designed to better integrate local knowledge and context-specificity of adaptation issues, such as through the inclusion of stakeholders during the modeling process. The merits of various decision-making processes toward quality decision-making in climate change adaptation for power systems also deserve thorough investigation.■

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Endnotes:

1. Documentation and other information about NEMS can be found at http://www.eia.gov/reports/index.cfm?t=Model%20Documentation.

2. A map of these regions can be viewed at http://www.epa.gov/cleanenergy/images/eGRID_subregions.gif.